Article

Hydropower scenarios in the face of climate change in Ecuador

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Abstract: Nowadays, hydropower is the principal renewable; however, climate change increases extreme events such as floods, droughts, erosion, and sedimentation of rivers that produce uncertainty in hydroelectric generation. Thus, this document aims to analyze the climate change projections in the hydropower systems of Ecuador based on data from 14 projects studying the scenarios according to the Shared Socioeconomic Pathways from the Intergovernmental Panel on Climate Change. The study period starts from 2010 to 2020 with historical data, collects the tendency, defines a database year, and then projects the scenarios to 2050. The quantitative methodology uses a statistic on Ecuador's hydropower obtained inflow time series to calculate the deviation over the last years and develop a model to simulate future generation. The results show that the hydropower in Ecuador is expected to decrease considerably through 2050 due to meteorological changes. In this calculation of the Shared Socioeconomic Pathways, the selected scenarios show a reduction in SSP5 of 11.5%, SP2 of 16.2%, and SSP4 of 18.2% to 2050, concluding that the opportunities for hydroelectric production facing climate change are variable, but the challenges are broad. In Ecuador, the projections of hydropower plants represent a sensitive issue of their reductions, especially knowing that the country had an energy grid in 2020 that depended on 87% of hydroelectric production.

Keywords: Climate change; Ecuador; energy; hydroelectric; pathways; renewable; scenarios.

1. Introduction

Globally, growing human demands for water and energy are expected to deal with difficulties in the coming decades [1]. Consequently, the worldwide shift to renewable energy production has increased the demand for new and more flexible operations practiced by organizations [2]. Nowadays, hydropower is the principal renewable; a sixth of global electricity production came from hydropower in 2020, making it the most significant low-carbon energy source combined with all other renewable sources [3], [4]. According to International Energy Agency, hydropower has grown in energy production in the last years, as Figure 1 shows.

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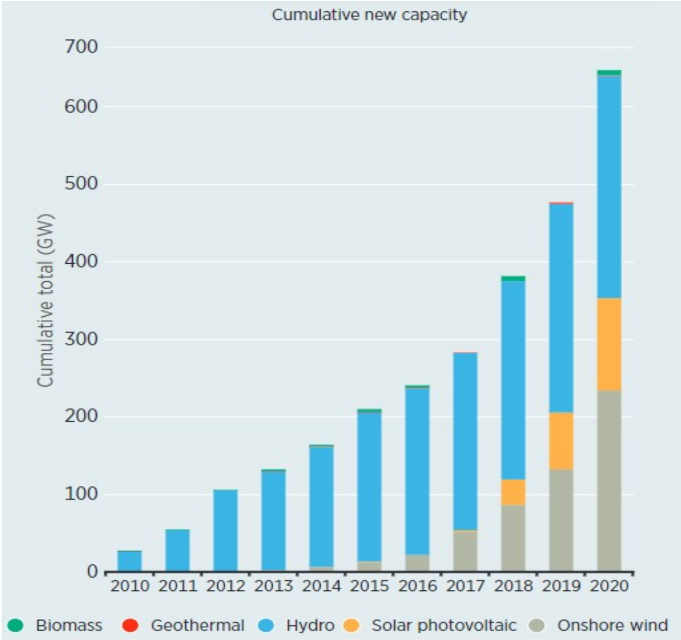

Figure 1. Global renewables generation 2010-2021. [5]

Figure 1 shows that hydropower has a vital shift component to clean sources today, including the quantities of low-carbon electricity and its unmatched capabilities for storing and securing this energy; thus, there is support for other renewables such as solar and wind, growing the last five years [6], [7].

Nevertheless, with renewable deployment, a negative part is spoken about; for example, hydropower interacts strongly with the environment due to its altering natural flows to produce energy. Hydropower depends on water, and the critical resource is rain, which depends on precipitation, but the future global climate is uncertain, causing a specific risk [8]. Consequently, it is essential to conduct an in-depth examination of these stations [9].

On the one hand, Ecuador is an excellent example of hydroelectric development because, in 2020, its energy grid was based on 87% of this source [10]. By the way, the government, despite being a country with abundant water, factors such as overuse, lousy distribution, and poor delivery of water use authorizations could trigger potential conflicts among citizens. As a reference, 88% of the Ecuadorian population lives in the Pacific basin, but the water availability is limited in this area, with only 31% of the water found there [11], [12].

Ecuador's geographical situation, climate, and natural resources determine favorable conditions for building new hydropower projects. However, it has yet to grow economically and even less from a sustainable perspective to ensure harmonious development [13]. Based on Carvajal's (2019) analysis of Ecuador's energy grid, it is clear that hydropower receives effects of climate change, thus with a partial equilibrium model for the energy system. It was found that the proportion of Ecuador's total electricity produced by hydropower could vary significantly by 2050 between 53% and 81%, and it could be attributed to a dry climate scenario, as well as social resistance that could limit the implementation of large-scale hydroelectric projects in the country [14].

However, between 2007 and 2017, nearly six billion dollars were invested in eight hydropower projects in Ecuador to harness the river currents and waterfalls, raising its capacity to around 2,832 MW [15], [16]. The Electric Corporation of Ecuador (CELEC in Spanish) established that there were 71 hydropower plants in operation by 2020 with 5,074 MW of installed capacity, compared to 2010 with 2,242 MW [17]. Therefore, there was an increase of 127% in hydropower installed capacity in ten years.

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According to the Ministry of the Environment, Water, and Ecological Transition of Ecuador, the country has taken essential steps to reduce its contribution to greenhouse gas emissions in electricity, especially with the increase of hydroelectric plants instead of polluting fossil sources [18]. Nevertheless, this country's millionaire endeavor may have some complications due to external factors. Ecuadorian and international scientists warn that hydropower plants are vulnerable to climate change, and the government has not made the necessary efforts to study this phenomenon [19], [20].

Hydropower generation is known to be one of the available low-carbon energy options; however, there are emerging problems due to its disorganized exploitation. Therefore, the issues arising from the intense hydropower generation must be highlighted with the understanding that the fluvial regimes are modified, and the local perceptions of the nearby communities where these projects are based are negative [21], [22].

On the other hand, hydropower projects need to improve efficiency due to the increasingly present meteorological variations. As a result of human-induced climate change, extreme events are more likely to occur, resulting in adverse impacts and damage to nature and people. There is a very high risk that climate change will hurt approximately 3.3 to 3.6 billion people, according to the Intergovernmental Panel on Climate Change (IPCC) [23], [24].

In the case of hydropower, seasonal changes in snow-dominated basins are expected to lead to an increase in winter and a decrease in production during the summer months. But, the melting of glaciers also influences the hydrological regimes, the sediment transport, the movement of natural species, and the dissipation of contaminants from rivers to the ocean, which has profound implications for ecosystem services, especially those related to water provision for agriculture, hydropower, and consumption [25], [26].

Historically, the rate of plant efficiency has been reduced by 4 to 5% during drought years compared to long-term average values since the 1980s, indicating a negative impact on current hydropower production due to droughts [23], [27].

The International Renewable Energy Agency (IRENA) establishes that between 2010 and 2020, the global weighted average power factor for hydroelectric changed from 51% in 2015 to 46% in 2020 in commissioned projects, which shows that hydropower is losing efficiency by around 1% per year by the climate change affections around the world [28], [29]. Therefore, to standardize the term power factor throughout the document, it is defined as a measure of the efficiency of an electrical system because it represents the performance and energy used to transform it into effort [30].

Climate change poses an increasing challenge to hydropower; an analysis of the International Energy Agency in 2020 establishes that until the end of the century, hydropower efficiency in Latin America is projected to decrease in all possible climate scenarios [31]. The impact of extreme climate events on hydropower production has been documented in numerous studies in the energy sector. However, limited studies measure trends in this energy production source due to long-term climate change, which is a knowledge gap.

Against this background, the novelty of this study presents an actual examination of the hydropower project's efficiency in a developing country with little investigation of this renewable source. Therefore, this manuscript aims to analyze the climate change projections in the hydropower systems of Ecuador based on power factor data from 14 hydro projects studying the possible future scenarios according to the Shared Socioeconomic Pathways from the Intergovernmental Panel on Climate Change.

2. Materials and Methods

It uses a quantitative methodology for the present analysis, with statistics and calculations on Ecuador's hydropower projects. While it obtains inflow time series for 14 hydropower stations in Ecuador using historical generation power factor data to undertake a comparison to the projection study. The next step is calculating the deviation over ten years as a tendency, selecting a robust data baseline (year to start), introducing the data in the platform (energy requirements, population, GDP, energy grid, hydropower capacity), calibrate the model with monthly hydropower production and meteorological data of temperature, and finally developing a model to simulate future hydropower production, as shown in the following figure the steps used.

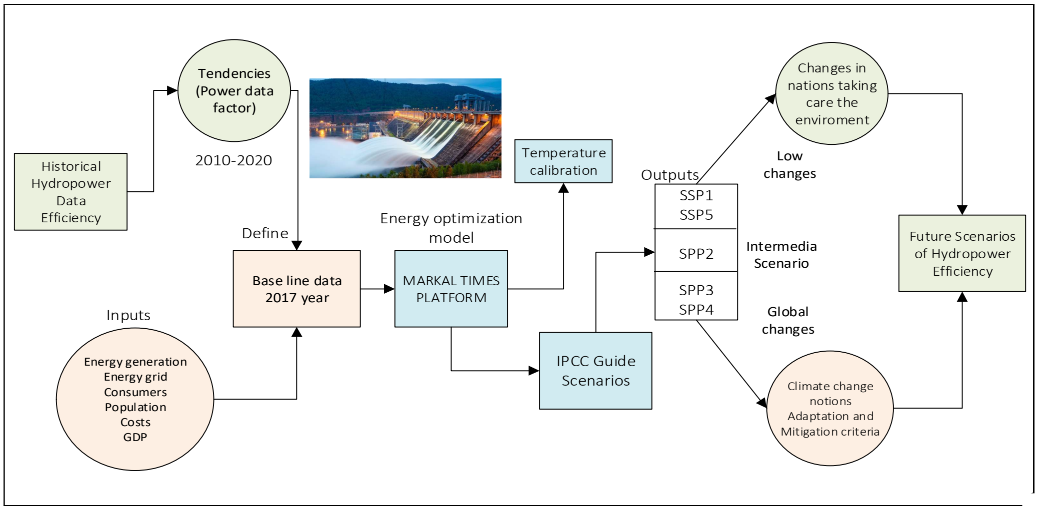

Figure 2. The methodology with Shared Socioeconomic Pathways scenarios.

Moreover, to collect the data on Ecuador, the primary data collection sources of the analysis that support this study are the following.

- The International Renewable Energy Agency
- Ministry of Environment, Water and Ecological Transition of Ecuador
- Ministry of Energy and Non-Renewable Resources of Ecuador
- The Electric Corporation of Ecuador

In the case of Ecuador, data will be tabulated on the power factor of the most representative hydropower plants (14) that add a capacity of 4,396 MW, representing 87% of the total 5,074 MW of installed generation reported in 2020 [17]. In addition, the information covers from 2010 to 2020, divided into two periods: 2010 to 2015 and 2016 to 2020.

It took the power factor as a measurable efficiency indicator in the electrical systems because this needle deals with the amount required to transform into effort [30]. In addition, the future scenarios were generated based on the IPCC concepts, presenting five evolutionary climate change lines where pronounced global and regional differences are marked and depend on the countries and world leaders' actions. Nowadays, these lines are called Shared Socioeconomic Pathways (SSP) [26].

These Shared Socioeconomic Pathways demonstrate possible scenarios that were captured in the IPCC Sixth Assessment Report on climate change in 2021 and describe alternative development in the following decades; for example, it proposes considering the economic evolution, future levels of inequality, demographic and technological changes, as shown in Figure 3.

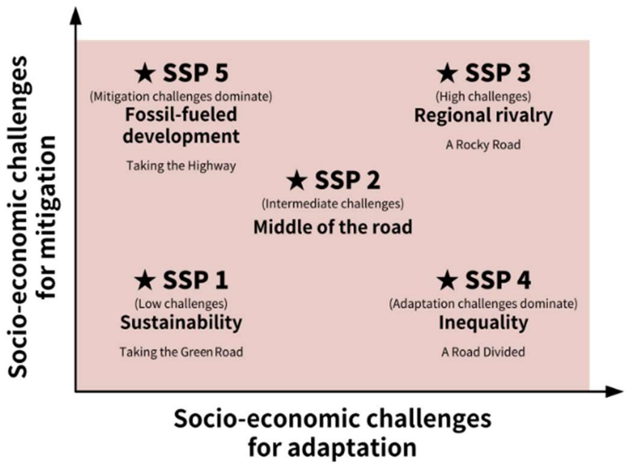

Figure 3. Shared Socioeconomic Pathways scenarios. (IPCC -ONU, 2019).

Since this study assesses the future challenges for hydropower deployment under different scenarios to compare their impacts, a power system optimization model called Markal-Times is used in this study. The platform structure depends on data incomes such as demographic distribution, electricity technologies, energy grid, and outcomes such as economic impacts, capital needs, and energy projections. Markal conducts data analyses with environmental perspectives and a historical energy database. The results of this examination are used to explore pathways based on contrasted scenarios of electricity production and consumption [33], [34].

The baseline year selected is 2017, when the average price of electricity in Ecuador billed to customers was 9.79 USD¢/kWh, and the national energy demand was 21,831 GWh. From the demand, a billing of 1,901,334 USD was collected [35], [36]. This year was selected due to its energy trend with a distribution of various primary sources; it is also a year before the 2019 COVID pandemic, where consumption values became atypical for the various sectors, which makes projections difficult due to variations that there were.

3. Results

3.1 Tendencies and Data

As mentioned, first, it shows the energy efficiency of the projects; according to The Electric Corporation of Ecuador, the power factor data from 14 hydropower plants related show the following trend over time (2010-2020), a similar period of the International Renewable Energy Agency analyzes (Table 4).

Table 1. Ecuador's power factor of hydropower in % (2010 - 2020)

Hydropower Projects	Power Factor (%)											Average 2010 - 2015	Average 2016 - 2020
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020		
Agoyán	66.95	68.43	72.05	74.17	71.46	80.55	72.63	70.00	65.77	71.49	69.11	72.3	69.80
Baba	-	-	-	-	-	-	42.50	36.00	28.25	41.00	46.02	-	38.75
Coca Codo Sinclair	-	-	-	-	-	-	48.51	45.00	46.59	48.05	51.91	-	48.01
Manduriacu	-	-	-	-	-	42.59	57.04	64.35	56.00	64.05	66.57	42.6	61.60
Marcel Laniado	41.47	35.23	56.33	44.64	50.82	55.73	60.89	58.17	48.34	63.37	46.40	47.4	55.43
Minas San Francisco	-	-	-	-	-	-	-	-	-	41.90	42.46	-	42.18

Paute Mazar	-	63.52	65.58	43.44	50.98	55.78	51.13	48.44	46.37	52.21	45.14	55.9	48.66
Paute Molino	42.02	60.70	64.25	54.43	55.73	64.39	54.81	48.07	51.13	58.22	53.94	56.9	53.23
Paute Sopladora	-	-	-	-	-	-	27.65	52.11	50.04	56.38	57.41	-	48.72
Pucará	-	24.37	6.85	29.46	40.36	47.35	43.07	31.18	33.24	39.28	37.90	29.7	36.93
San Francisco	56.05	49.05	69.81	75.10	71.50	80.03	61.80	52.39	41.23	55.41	66.89	66.9	55.54
Saucay	48.36	68.17	66.43	54.85	56.14	67.87	55.47	52.58	47.73	51.49	54.28	60.3	52.31
Sayamirin	56.60	77.22	76.53	63.43	64.35	73.85	63.97	60.34	57.49	25.50	40.08	68.7	49.48
Sibimbe	63.26	70.26	66.21	56.40	67.20	72.88	67.00	67.29	54.99	64.42	66.04	66.0	63.95
Average						**53.04**						**56.67**	**51.76**

Source: [17], [37].

From Table 1, it is observed that there are periods when there are no data; it is because the projects were not in operation; as mentioned in about the last 13 years, it is the stage when hydropower in Ecuador overgrew. The statistics are divided into 5-year periods to calculate an average. In the comparison period of 2010-2015 and 2016-2020, a -4.90% reduction in power factor is presented. The value represents a variation decrease of 9.4% between the two periods; Summarizing in 10 years, hydropower projects lose efficiency by 0.5% annually. Followed a map of the total Ecuadorian hydropower projects around the country.

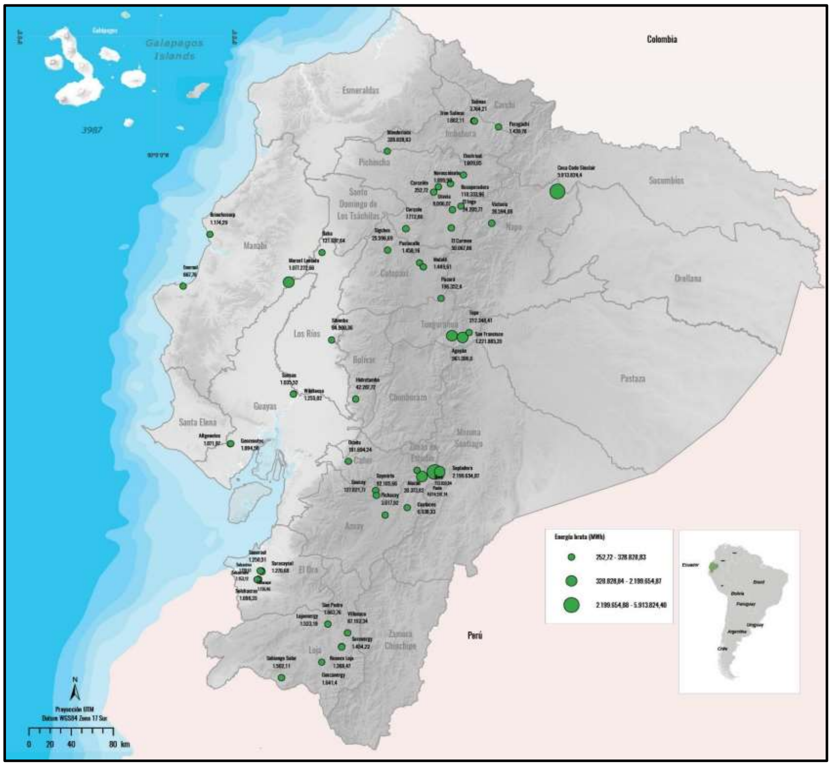

Figure 4. Ecuadorian hydropower projects. [38]

On the other hand, in the context of the Ecuadorian energy grid to the projection, the Markal - TIMES model minimizes the costs associated with installing the technologies necessary to meet the electricity demand. Consequently, certain processes are involved in developing SSPs and modeling scenarios. Then, using the baseline year and input data table, it was projected on the platform, guiding quantitative interpretations and scenario assumptions related to resource availability, technological advancements, and energy demand drivers.

Inputs data

In 2017, the generation capacity of Ecuador registered 8,036 MW of nominal power and 7,435 MW of effective power. The nominal power of 4,716 MW (58.67%) corresponded to plants with renewable and 3,321 MW (41.33%) to plants with non-renewable energy sources. Of the 4,716 MW of renewable energy, 96% corresponds to hydropower. Furthermore, to the total distribution of electricity in the country, 104 plants are renewable and 193 thermals, giving 297 electrical projects distributed in 23 provinces. The highest concentration of power is found in Azuay, Napo, and Guayas provinces, predominantly renewable generation plants in the first two. In addition, the average power factor or efficiency of the 14 projects for 2017 was 52.76 [39], [40].

Moreover, 102 MW of new energy were added in this baseline year, of which 98% was in hydropower. Also, Ecuadorian regulated clients by energy consumption group, 88% represent the residential sector, 9% are from the commercial sector, and the rest belong to the industrial and public lighting sector (3%). Further information from the National Institute of Statistics and Censuses of Ecuador in 2017 had a population of 16.7 million inhabitants, and to cover the energy need, the production of gross energy for that year was 20,089 GWh of hydroelectricity (72%), wind 73 GWh (0.3%), photovoltaic 37 GWh (0.13%), biogas 28 GWh (0.10%), biomass 431 GWh (1.5%), and for the thermal part in internal combustion engines 4,439 GWh (16%), Turbo-gas 1,644 GWh (6%), and Turbo-steam 1,292 GWh (4%) [40], [41].

Outputs data

According The Electric Corporation of Ecuador the remaining hydropower capacity expansion potential in Ecuador under the inventory of projects for a short time (4-5 years to 2028 approximately), which is planned in 645 MW for 14 projects (hydropower and other renewable energies). Of the 14 projects under construction, 11 correspond to hydropower projects with 407.5 MW, that is, 63% of the planning, two thermoelectric projects with a capacity of 187 MW, and one wind power project with a power of 50 MW. In addition, Ecuador has great potential, mostly for large hydropower projects in the medium term (6-10 years to 2033 approximately) to Rio Santiago (2,600 MW) and Cardenillo (596 MW) projects [35].

Moreover, from the Shared Socioeconomic Pathways of IPCC to model hydropower demand evolution in Ecuador, a single projection assumes annual growth rates of the population of 1.37% and Gross Domestic Product (GDP) of 2.7% [42], [43]. Meanwhile, Markal-Times' model articulates the international trajectory to reduce greenhouse gas emissions. Therefore, the study considers that globally, it needs to keep its emissions below 1.5 degrees Celsius by 2050.

3.2 The Ecuadorian projection

To start the model evaluation in Markal, it compares the observed temperature for the calibration periods from 1981 to 2017 at six hydrologic stations in Ecuador (Lumbaqui, Baños, Paute, Sangay, Puerto Ila, and Babahoyo). These meteorological stations are related to the main distribution of hydropower production in the Azuay, Napo, Tungurahua, and Cañar provinces in Ecuador as represented in Figure 5.

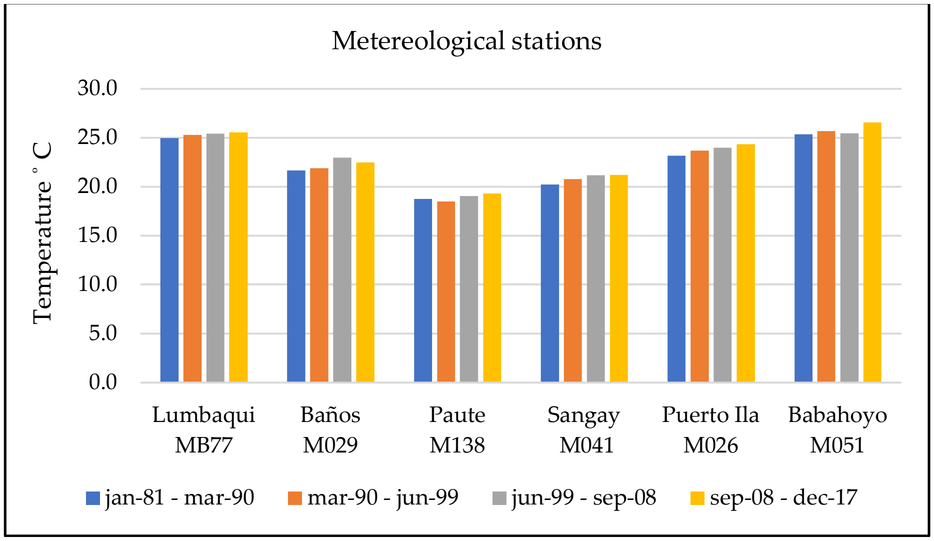

Figure 5. Ecuadorian principal six meteorological stations. [44]

It took the meteorological stations related to these main hydropower provinces. The results demonstrate that the simulated series matched the observed series well, and all the station's present temperature variations increased in 2017. The reasons for this phenomenon arise from the high intensity of human activities in these places that build the hydropower projects; the conditions change, showing the climate change impacts. In addition to the database year that it took, the monthly hydropower generation is represented as the next figure to calibrate the distribution of energy.

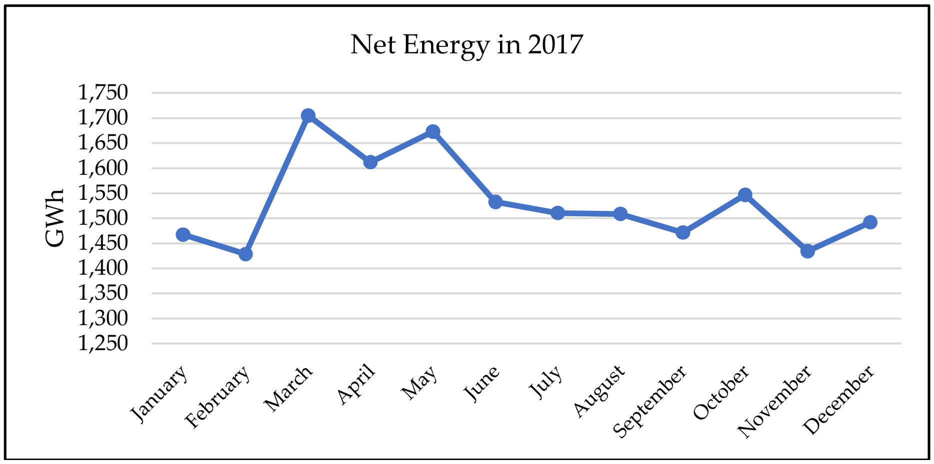

Figure 6. Net hydropower delivered per month in Ecuador. [44]

Ecuador has a strategic capacity in relation to hydroelectric projects thanks to its tropical climate and water tributaries that do not vary greatly throughout the year, however, as the figure shows, there are months with a reduction in potential, this is because, although it is a tropical climate in summer seasons (June-August) there are climates without much precipitation which affects hydroelectric generation [45].
Following the data projection of energy efficiency to 2050, the main socioeconomic drivers, i.e., population, economic activity, and energy grid, are translated into quantitative scenarios. It was done to derive in a model of hydropower power factor of the energy, and emissions associated with SSPs as show in the Figure 7.

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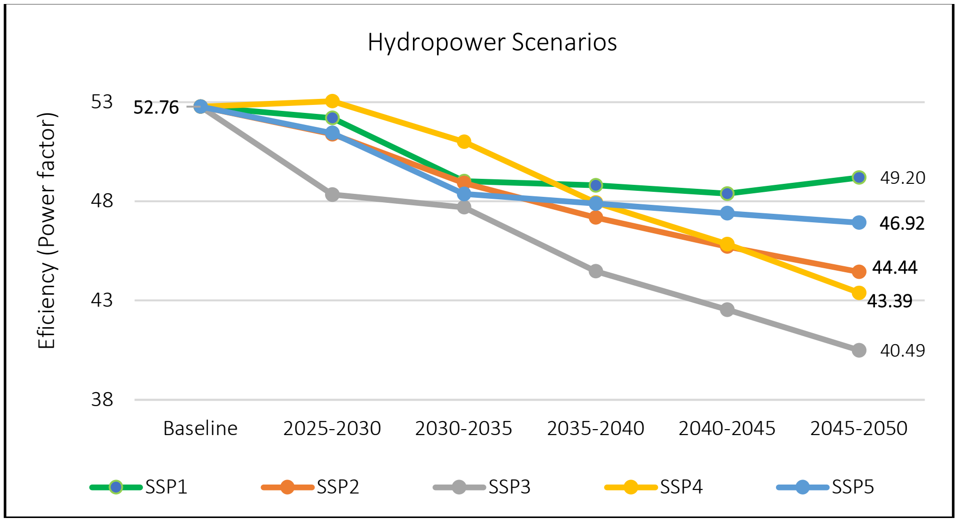

Figure 7. Ecuadorian efficiency hydropower scenarios to 2050.

Based on the present researcher's criterion of the five Shared Socioeconomic Pathways, it selects the efficiency projection of SSP2, SSP4, and SSP5, believing that these scenarios have a central related tendency to 2050 and the reasons for **Table 2** that mention the applied criteria, analyzing the regional and global renewables tendencies.

Table 2. Selected scenarios from the Shared Socioeconomic Pathways

No.	Pathway	Global Context	Definitions
1	SSP2	This model assumes that social, economic, and technological trends will remain the same from historical patterns, leading to a high GDP growth, which may take more work to maintain consistently over the next few decades. The degree of inequality is maintained, but some nations are making relatively good progress, whereas others need to meet expectations [46].	Intermedia scenario of challenges is the moderate projection
2	SSP4	The evolutionary line requires high challenges for adaptation and low for mitigation; it represents a mixed tendency is a fragmented projection guided by various changes and presents a difficult path to meet the global goals of maintaining the temperature and socioeconomic development as a result of economic slowdown, material-intensive consumption, and slow economic growth [47].	Global high changes but development fragmentation
3	SSP5	It has high challenges for mitigation, low for adaptation, and energy demand is high in the absence of climate policy, and carbon-based fuels meet most of this demand due to the need for climate policies. This pathway incorporates as convenient occasional partnerships, and the government leadership has proposed planning on climate change that needs to be more comprehensive [48].	Mitigation Challenges dominate the tendency.

As shown in **Table 2** and IPCC concepts, the selection of SSP2, SSP4, and SSP5 are because the characteristics are based on the capital cost, which serves as a key factor in siting and construction of facilities. On the other hand, they chose scenarios where population growth is high in developing countries [49], [50].

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In contrast, the pathways SSP1 and SPP3 on the Sixth Assessment Report are little evaluated by the complication of joining other models, assumptions, and driving forces, for example, the Representative Concentration Pathways (RCPs) and Global Warming Levels (GWLs) [23]. In addition, it isn't very easy globally as the SSP1 is present because a sustainable way with a green road belief is not projected. Moreover, in the SSP3 scenario, it does not trust to do next year and is certain it is dreadful only to be on adaptation challenges with total inequality. Therefore, it does not select scenarios: SSP1 and SSP3 because these two are the extreme tendencies illustrated in Figure 7.

As a result of the analysis, the methodology identifies three scenarios for future hydropower efficiency that capture a range of challenges that must be addressed. The projections represent an evolution of relative fluctuations due to changes in technology and another with medium-sized changes anchored to medium-sustainable development, for which the factors that determine the progress of climate change are related to each scenario, and there is an uncertainty associated with the evolution of the socioeconomic and meteorological system of Ecuador. Moreover, the results determine the variation and difference of the scenarios modeled in Markal – Times software giving the resume in **Table 3**.

Table 3. Ecuadorian power factor variations to 2050

Average	Period 2010 - 2020	SPP5 scenario to 2050	SPP2 scenario to 2050	SPP4 scenario to 2050
14 Hydropower projects	53.04	46.92 (-6.12)	44.44 (-8.6)	43.39 (-9.65)
Percentage variation	-	-11.5%	-16.2%	-18.2%

4. Discussion

Hydropower is a capital-intensive technology that requires long lead periods for its installation. These lead times include allowing, site construction, and commissioning. The projects are large and complex, involving significant changes to civil engineering, lengthy site surveys, inflow data collection, environmental assessments, and any permits required to move forward with the project [51], [52]. Therefore, they are often not the best investment decision, as shown by the global efficiency reductions in Table 4.

Moreover, according to **Table 1**, in contrast, Killingtveit mentions that hydropower plants have up to 70% average efficiency [53]. Alternatively, Denisov mentions that the advantages of hydroelectric stations are the high coefficient of power factor, which amounts to 62-82%, compared to about 33% for nuclear and thermal power stations [54].

Although hydropower is a mature technology widely used among renewables, IRENA determines that global share has slowly declined. The percentage of hydropower among renewables fell from 72% of the share in 2010 (881 GW) to 41% of the share in 2020 (1,153 GW), excluding pumped hydroelectricity, despite the increase installed [55], [56].

Thus, comparing the hydropower plant's performance in Ecuador with data from IRENA, it is clear that the projects have the same marked global effects that vary the net potential, decreasing the efficiency due to the various changes in the climatic seasons at a worldwide level, as shown in **Table 3**. Therefore, it is important to discuss that IRENA determines a reduced tendency in large-scale hydropower projects (≥ 200 MW) and small-scale over ten years, calculating the differences between periods (2010/2015 – 2016/2020) in an average percentage variation of -7.5% such as shown **Table 4** [55].

Corroborating the results, a study has been carried out on the sensitivity to climate change in the Ecuadorian hydroelectric sector, including in five basins: Coca, Toachi Pilaton, Paute, Jubones, and Zamora, under the conception that these basins contain the majority of hydropower projects showing a wide range of uncertainty and irregular production, the results show a wide annual inflow variation, and the annual hydroelectric power production in Ecuador is found to reduce between 55% and 39% of the mean historical

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output for 2071–2100 [57]. Another study of Ecuadorian projects mentions that the total amount of electricity supplied by hydropower is expected to vary significantly between 53% and 81% by 2050, similar to the results of this tendency shown in **Table 3** of efficiency reduction [16].

Furthermore, data from the Nationally Determined Contributions of Ecuador regulates that there are expected impacts related to the lack of rainfall that is accentuated in the central areas of the coast, central and south of Sierra, and Amazonas zones when there is the central part of hydropower projects and when before it was a rainy place [18], [58]. In light of these circumstances, studies of the climate change effects on hydrological variability and energy capacity need to be a priority research area in Ecuador.

According to Parra (2020), hydropower designs in Ecuador would have needed to consider vulnerability to climate change sufficiently. Hydroelectricity has a fundamental role in Ecuadorian energy policy to achieve the goals of reducing greenhouse gas emissions, a great challenge for the country's balance between economic development and responsible energy generation. However, long-term climate changes can disturb the function of these plants in favor of energy production and the environment [59].

Comparing the calculated results of Ecuador (**Table 3**) with other studies, for example, in Colombia, a multimodal investigation was generated on climate change and hydropower, the neighboring country with similar climate characteristics detected that water disposal in some regions would be affected, and hydroelectric production will vary affording to models for the next three decades. The models found that weather-related losses in hydropower from 2015 to 2029 will reduce the generation capacity between 5.5% and 17.1% [60], [61]. On the other hand, another example of climate change analysis by the World Bank in Vietnam, which did a study of the hydropower projects' feasibility, including climate change sensitivity tests, and analyzed the impacts on generation; in this specific case of the Asian country, hydropower generation would fall in the next 25 years by a significant amount, up to 36% of the projected due to climate variability, because the climate modifications occasion the hydropower efficiency decrease, similar results as Ecuador to 2050 decreasing for the projected scenarios [62], [63].

According to Hamududu, based on 12 global circulation models, some notable changes in runoff will expect significant decreases in some countries affecting hydropower generation. The models show that by 2050, in the south and north of Africa, hydropower production can be declined by -0.48% and -0.83%, respectively. Western Asia can reduce by -1.43%, and Europe has around a -2% reduction [8].

In summarizing, as shown by the results, over ten years, the hydropower in Ecuador presents traces of climate change, knowing that projects reduced their efficiency. Climate change can alter hydropower production capacity with high variance [64]. From any field transitions, the electricity sector requires a focus on climate change adaptation and a specific study on hydropower by their representative. This established technology contributes to climate change mitigation, but there are substantial environmental, cultural, climatic, and social costs [65], [66].

On the other hand, there are exceptionalities to this study, for example, that it projects future scenarios that are difficult to predict and that constantly change; therefore, with the presence of several variables of a base year, future results are sought; however, the scope of this analysis provides recommendations for future studies to be carried out at the Ecuadorian level, and as a basis for other countries where their energy source is related to hydroelectricity.

By using more hydropower, greenhouse gas emissions will be lower. Nevertheless, the problem is that the country should not only worry about lowering these emissions but also work on energy efficiency as the results of Ecuador and other studies can see that climate change is a complex issue; future lines can analyze the power factor and tendency since the '50s of the other renewables technologies to develop an expansion policy in the different regions globally sustainably and efficiently, making recommendations according to the historical data of all renewables.

5. Conclusions

Constructing the hydropower scenarios in the face of climate change in Ecuador, it uses a historical efficiency of 14 projects, defines 2017 as a database year with the information on the energy grid, and projects the IPCC criteria in the possible hydropower tendencies related to the Shared Socioeconomic Pathways with the Markal Times platform.

The hydropower efficiency in Ecuador is calculated to decrease considerably through 2050 due to meteorological changes. In this calculation of the Shared Socioeconomic Pathways, the three selected scenarios show a reduction in SSP5 of 11.5%, SSP2 of 16.2%, and SPP4 of 18.2%, concluding that the opportunities for hydropower production facing climate change are variable in Ecuador, but the challenges are broad.

In Ecuador, from 2010 to 2020, this study shows a decreasing efficiency of 0.5% annually in 14 projects analyzed, presenting significant variations to their potential. Hydropower generation shows an uncertain and sensitive issue to climate change, especially knowing that the country had an energy grid in 2020 with around 87% hydroelectric production, which can represent a future challenger.

In Ecuador, rapid and aggressive hydropower construction has changed the energy grid in the last fifteen years. Still, this renewable production is vulnerable to climate change impact, according to the 14 projects analyzed. Thus, before considering dam construction, it is necessary to explore the future hydropower efficiency with more accurate decisions, promoting the development of other non-conventional renewable sources that avoid climate change in the coming years.

The present study is just a small example of a developing country with a representative number of hydropower projects; an analysis of the countries with the biggest installed hydropower capacity is necessary to know the approach of the source taking data from efficiency, energy production, and climate parameters to make the best future investment decisions.

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Appendix

According to IRENA, Table 4 presents a relationship between the hydropower global power factor trends from 2010 to 2020.

Table 4. Worldwide power factor of hydropower by region in % (2010 - 2020)

No.	Region	Average (%). Large hydropower		Average (%). Small hydropower	
		2010-2015	2016-2020	2010-2015	2016-2020
1	Africa	47	55	56	55
2	Brazil	61	45	63	56
3	Central America	48	53	59	-
4	China	45	47	46	38
5	Eurasia	43	42	58	61
6	Europe	41	33	48	44

7	India	47	42	50	57
8	Other Asia	46	50	80	54
9	Other South America	62	60	65	-
	Average	**48.89**	**47.44**	**58.33**	**52.14**
	Variation (%)	**- 3.0%**		**- 11.9%**	
	Average	**-7.45%**			

Source: [55].

References

[1] N. Johnson *et al.*, "Integrated solutions for the water-energy-land nexus: Are global models rising to the challenge?," *Water (Switzerland)*, vol. 11, no. 11, p. 33, 2019, doi: 10.3390/w11112223.

[2] A. P. Eloranta, A. G. Finstad, I. P. Helland, O. Ugedal, and M. Power, "Hydropower impacts on reservoir fish populations are modified by environmental variation," *Science of the Total Environment*, vol. 618, pp. 313–322, 2018, doi: 10.1016/j.scitotenv.2017.10.268.

[3] S. Cabrera *et al.*, "Variations in benthic macroinvertebrate communities and biological quality in the aguarico and coca river basins in the ecuadorian amazon," *Water (Switzerland)*, vol. 13, no. 12, pp. 1–26, 2021, doi: 10.3390/w13121692.

[4] S. Naranjo-Silva and J. Alvarez del Castillo, "The American Continent hydropower development and the Sustainability: A Review," *International Journal of Engineering Science Technologies*, vol. 6, no. 2, pp. 66–79, Apr. 2022, doi: 10.29121/ijoest.v6.i2.2022.315.

[5] International Energy Agency, "Hydropower Special Market Report. Analysis and forecast to 2030," 2022. [Online]. Available: www.iea.org/t&c/

[6] A. Lohrmann, M. Child, and C. Breyer, "Assessment of the water footprint for the European power sector during the transition towards a 100% renewable energy system," *Energy*, vol. 233, p. 121098, 2021, doi: 10.1016/j.energy.2021.121098.

[7] C. Llamosas and B. K. Sovacool, "The future of hydropower? A systematic review of the drivers, benefits and governance dynamics of transboundary dams," *Renewable and Sustainable Energy Reviews*, vol. 137, no. 0321, pp. 110–124, 2021, doi: 10.1016/j.rser.2020.110495.

[8] B. Hamududu and A. Killingtveit, "Assessing climate change impacts on global hydropower," *Energies (Basel)*, vol. 5, no. 2, pp. 305–322, 2012, doi: 10.3390/en5020305.

[9] A. Briones Hidrovo, J. Uche, and A. Martínez-Gracia, "Determining the net environmental performance of hydropower: A new methodological approach by combining life cycle and ecosystem services assessment," *Science of the Total Environment*, vol. 712, p. 44, 2020, doi: 10.1016/j.scitotenv.2019.136369.

[10] S. Naranjo-Silva, J. Punina, and J. Álvarez Del Castillo, "Comparative cost per kilowatt of the latest hydropower projects in Ecuador," *InGenio Journal*, vol. 5, no. 1, pp. 1–14, 2022, doi: 10.18779/ingenio.v5i1.473.

[11] G. Escribano, "Ecuador's energy policy mix: Development versus conservation and nationalism with Chinese loans," *Energy Policy*, vol. 57, pp. 152–159, 2013, doi: 10.1016/j.enpol.2013.01.022.

[12] M. A. Ponce-Jara, M. Castro, M. R. Pelaez-Samaniego, J. L. Espinoza-Abad, and E. Ruiz, "Electricity sector in Ecuador: An overview of the 2007–2017 decade," *Energy Policy*, vol. 113, no. August 2017, pp. 513–522, 2018, doi: 10.1016/j.enpol.2017.11.036.

[13] P. Reyes *et al.*, "Exceptionally uncommon overburden collapse behind a natural lava dam: Abandonment of the San-Rafael Waterfall in northeastern Ecuador," *J South Am Earth Sci*, vol. 110, no. April, p. 103353, Oct. 2021, doi: 10.1016/j.jsames.2021.103353.

[14] P. E. Carvajal and F. G. N. Li, "Challenges for hydropower-based national determined contributions: a case study for Ecuador," *Climate Policy*, vol. 19, no. 8, pp. 974–987, 2019, doi: 10.1080/14693062.2019.1617667.

[15] MERNNR, "National Energy Efficiency Plan," *2018*, 2018. https://www.celec.gob.ec/hidroagoyan/images/PLANEE_INGLES/NationalEnergyEfficiencyPlan20162035_2017-09-01_16-00-26.html

[16] P. E. Carvajal, F. G. N. Li, R. Soria, J. Cronin, G. Anandarajah, and Y. Mulugetta, "Large hydropower, decarbonisation and climate change uncertainty: Modelling power sector pathways for Ecuador," *Energy Strategy Reviews*, vol. 23, no. January, pp. 86–99, 2019, doi: 10.1016/j.esr.2018.12.008.

[17] CELEC, "CELEC EP genera y transmite más del 90 por ciento de la energía eléctrica limpia que consume el país y exporta a los países vecinos," 2020. https://www.celec.gob.ec/hidroagoyan/index.php/sala-de-prensa/noticias/722-celec-ep-genera-y-transmite-mas-del-90-por-ciento-de-la-energia-electrica-limpia-que-consume-el-pais-y-exporta-a-los-paises-vecinos#:~:text=En este sentido%2C de la,a través de cen (accessed May 22, 2021).

[18] Ministry of Environment and Water of Ecuador, "First Contribution Determined at the National Level to the Paris Agreement under the United Nations Framework Convention on Climate Change," Quito, 2019. Accessed: Sep. 09, 2022. [Online]. Available: https://www.ambiente.gob.ec/wp-content/uploads/downloads/2022/02/Folleto-NDC-2020-2025.pdf

[19] S. Vaca-Jiménez, P. W. Gerbens-Leenes, and S. Nonhebel, "The water footprint of electricity in Ecuador: Technology and fuel variation indicate pathways towards water-efficient electricity mixes," *Water Resour Ind*, vol. 22, no. June, p. 100112, 2019, doi: 10.1016/j.wri.2019.100112.

[20] M. M. Hasan and G. Wyseure, "Impact of climate change on hydropower generation in Rio Jubones Basin, Ecuador," *Water Science and Engineering*, vol. 11, no. 2, pp. 157–166, 2018, doi: 10.1016/j.wse.2018.07.002.

[21] A. M. Mayeda and A. D. Boyd, "Factors influencing public perceptions of hydropower projects: A systematic literature review," *Renewable and Sustainable Energy Reviews*, vol. 121, no. March 2019, p. 109713, 2020, doi: 10.1016/j.rser.2020.109713.

[22] N. Sahu, T. Sayama, A. Saini, A. Panda, and K. Takara, "Understanding the hydropower and potential climate change impact on the himalayan river regimes—a study of local perceptions and responses from himachal pradesh, india," *Water (Switzerland)*, vol. 12, no. 10, Oct. 2020, doi: 10.3390/w12102739.

[23] Intergovernmental Panel on Climate Change, "IPCC AR6 Working Group II Report," 2021. Accessed: May 15, 2022. [Online]. Available: https://www.ipcc.ch/assessment-report/ar6/

[24] M. M. Uamusse, K. Tussupova, and K. M. Persson, "Climate change effects on hydropower in Mozambique," *Applied Sciences (Switzerland)*, vol. 10, no. 14, 2020, doi: 10.3390/app10144842.

[25] O. Edenhofer *et al.*, "Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change," Cambridge, 2011. doi: 10.1017/CBO9781139151153.

[26] IPCC-IPBES, "Scientific outcome - Biodiversity and Climate Change," 2020.

[27] IPCC *et al.*, "Resumen para Políticas Responsables de los Expertos sobre Cambio Climático," New York, 2007. Accessed: Jun. 20, 2022. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SPM_version_report_LR.pdf

[28] IRENA, "Renewable Energy Statistics 2020. Renewable hydropower (including mixed plants)," 2020.

[29] L. Sun, Y. Cai, A. Chen, D. Zamora, and F. Jaramillo, “Water footprint and consumption of hydropower from basin-constrained water mass balance,” *Adv Water Resour*, vol. 153, no. May, p. 103947, 2021, doi: 10.1016/j.advwatres.2021.103947.

[30] G. L. T. Filho, I. F. Silva dos Santos, and R. M. Barros, “Cost estimate of small hydroelectric power plants based on the aspect factor,” *Renewable and Sustainable Energy Reviews*, vol. 77, no. March, pp. 229–238, 2017, doi: 10.1016/j.rser.2017.03.134.

[31] International Energy Agency, “Renewables, analysis and forecast to 2025,” vol. 74, no. 9, pp. 56–57, 2020, doi: 10.1002/peng.20026.

[32] IPCC -ONU, *Calentamiento Global de 1,5 °C*. Wallington, 2019. [Online]. Available: https://www.un.org/es/global-issues/climate-change

[33] M. Bongio, F. Avanzi, and C. De Michele, “Hydroelectric power generation in an Alpine basin: Future water-energy scenarios in a run-of-the-river plant,” *Adv Water Resour*, vol. 94, pp. 318–331, 2016, doi: 10.1016/j.advwatres.2016.05.017.

[34] S. Calderón *et al.*, “Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets,” *Energy Econ*, vol. 56, pp. 575–586, 2014, doi: 10.1016/j.eneco.2015.05.010.

[35] Ministry of Energy and Non-Renewable Resources of Ecuador, “Master Plan of Electricity 2019-2027,” 2019. [Online]. Available: https://www.recursosyenergia.gob.ec/plan-maestro-de-electricidad/

[36] L. Rivera-González, D. Bolonio, L. F. Mazadiego, S. Naranjo-Silva, and K. Escobar-Segovia, “Long-term forecast of energy and fuels demand towards a sustainable road transport sector in Ecuador (2016-2035): A LEAP model application,” *Sustainability (Switzerland)*, vol. 12, no. 2, pp. 1–26, 2020, doi: 10.3390/su12020472.

[37] Ministerio de Energía y Recursos Naturales No Renovables, “Desarrollo hidroeléctrico del Ecuador y cambio climático,” no. 811. Quito, pp. 1–2, 2020.

[38] Open Street Map, “Location of Ecuadorian hydroelectric plants,” 2022. https://www.openstreetmap.org/note/2721104#map=6/-0.754/-73.334

[39] J. Hartmann, “Climate Change and Hydropower Training Manual. AICCA Project, Ministry of the Environment and Water of Ecuador - CONDESAN.” p. 1012, 2020. [Online]. Available: https://condesan.org/recursos/manual-entrenamiento-cambio-climatico-e-hidroenergia/

[40] Ministry of Energy and Non-Renewable Resources of Ecuador, “The Gained Decade of the Electricity Sector in Ecuador,” Quito, 2017.

[41] G. Poveda-Burgos, Z. N. F. Castañeda, E. Á. E. Flores, K. R. Molina, and J. G. Ruiz, “Desarrollo local de la nueva matriz energética en el Ecuador desde Coca Codo Sinclair,” *Oidles*, vol. 22, pp. 114–144, 2017, [Online]. Available: http://www.eumed.net/rev/oidles/22/coca-codo-sinclair.html

[42] The World Bank, “Population estimates and projections,” 2021. https://databank.worldbank.org/source/population-estimates-and-projections

[43] The World Bank, “GDP per capita (current US$),” 2021. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?end=2020&locations=BR-EC-CO&start=2000&view=chart

[44] Ministry of Energy and Non-Renewable Resources of Ecuador, “Atlas of the Ecuadorian electricity sector,” 2017. Accessed: Apr. 13, 2023. [Online]. Available: https://www.controlrecursosyenergia.gob.ec/wp-content/uploads/downloads/2020/08/atlas%20reducido.pdf

[45] D. Villamar *et al.*, “Long-term deep decarbonisation pathways for Ecuador: Insights from an integrated assessment model,” *Energy Strategy Reviews*, vol. 35, no. April 2020, p. 100637, 2021, doi: 10.1016/j.esr.2021.100637.

[46] A. F. P. Lucena *et al.*, "Interactions between climate change mitigation and adaptation: The case of hydropower in Brazil," *Energy*, vol. 164, pp. 1161–1177, 2018, doi: 10.1016/j.energy.2018.09.005.

[47] D. Villamar, R. Soria, M. Império, and P. Carvajal, "Deep Decarbonizatoin Pathways in Latin America and the Caribbean - A case study in Ecuador," in *Conference: 7th ELAEE Buenos Aires 2019 Decarbonization, Efficiency and Affordability: New Energy Markets in Latin America at Buenos Aires, Argentina New Energy Markets in Latin America at Buenos Aires, Argentina*, Buenos Aires, 2019, pp. 1–9.

[48] K. Riahi *et al.*, "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview," *Global Environmental Change*, vol. 42, pp. 153–168, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.05.009.

[49] N. B. Choudhury and S. R. Dey Choudhury, "Implications for planning of hydroelectric projects in Northeast India: an analysis of the impacts of the Tipaimukh project," *GeoJournal*, vol. 8, no. Wcd 2000, p. 21, 2020, doi: 10.1007/s10708-020-10158-8.

[50] Y. Yao *et al.*, "Responses of hydrological processes under different shared socioeconomic pathway scenarios in the Huaihe river basin, China," *Water (Switzerland)*, vol. 13, no. 8, Apr. 2021, doi: 10.3390/w13081053.

[51] S. Naranjo-Silva and J. Álvarez del Castillo, "Hydropower: Projections in a changing climate and impacts by this 'clean' source," *CienciAmérica*, vol. 10, no. 2, p. 32, Jul. 2021, doi: 10.33210/ca.v10i2.363.

[52] N. Hofstra, C. Kroeze, M. Flörke, and M. T. Van Vliet, "Editorial overview: Water quality: A new challenge for global scale model development and application," *Curr Opin Environ Sustain*, vol. 36, pp. A1–A5, 2019, doi: 10.1016/j.cosust.2019.01.001.

[53] A. Killingtveit, "Hydropower," in *Managing Global Warming: An Interface of Technology and Human Issues*, 2018, pp. 265–315. doi: 10.1016/B978-0-12-814104-5.00008-9.

[54] S. E. Denisov and M. V. Denisova, "Analysis of Hydropower Potential and the Prospects of Developing Hydropower Engineering in South Ural of the Russian Federation," *Procedia Eng*, vol. 206, pp. 881–885, 2017, doi: 10.1016/j.proeng.2017.10.567.

[55] IRENA, *Renewable Power Generation Costs in 2020*. 2021.

[56] S. Llerena-Montoya *et al.*, "Multitemporal analysis of land use and land cover within an oil block in the Ecuadorian Amazon," *ISPRS Int J Geoinf*, vol. 10, no. 3, 2021, doi: 10.3390/ijgi10030191.

[57] P. E. Carvajal, G. Anandarajah, Y. Mulugetta, and O. Dessens, "Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble—the case of Ecuador," *Clim Change*, vol. 144, no. 4, pp. 611–624, Oct. 2017, doi: 10.1007/s10584-017-2055-4.

[58] S. Vaca-Jiménez, P. W. Gerbens-Leenes, and S. Nonhebel, "The monthly dynamics of blue water footprints and electricity generation of four types of hydropower plants in Ecuador," *Science of the Total Environment*, vol. 713, p. 136579, 2020, doi: 10.1016/j.scitotenv.2020.136579.

[59] R. Parra, "Contribution of Non-Renewable Sources for limiting the electrical Co2 Emission Factor in Ecuador," 2020, pp. 1–33.

[60] O. J. Guerra, D. A. Tejada, and G. V. Reklaitis, "Climate change impacts and adaptation strategies for a hydro-dominated power system via stochastic optimization," *Appl Energy*, vol. 233–234, no. September 2018, pp. 584–598, 2019, doi: 10.1016/j.apenergy.2018.10.045.

[61] S. Arango-Aramburo *et al.*, "Climate impacts on hydropower in Colombia: A multi-model assessment of power sector adaptation pathways," *Energy Policy*, vol. 128, no. December 2018, pp. 179–188, 2019, doi: 10.1016/j.enpol.2018.12.057.

[62] The World Bank, "The World Bank Analyzes of Vietnam Sustainable Development Sector," 2011.

[63] K. Aroonrat and S. Wongwises, "Current status and potential of hydro energy in Thailand: A review," *Renewable and Sustainable Energy Reviews*, vol. 46, pp. 70–78, 2015, doi: 10.1016/j.rser.2015.02.010.

[64] J. L. Chiang, H. C. Yang, Y. R. Chen, and M. H. Lee, "Potential impact of climate change on hydropower generation in southern Taiwan," *Energy Procedia*, vol. 40, pp. 34–37, 2013, doi: 10.1016/j.egypro.2013.08.005.

[65] G. Ardizzon, G. Cavazzini, and G. Pavesi, "A new generation of small hydro and pumped-hydro power plants: Advances and future challenges," *Renewable and Sustainable Energy Reviews*, vol. 31, pp. 746–761, 2014, doi: 10.1016/j.rser.2013.12.043.

[66] G. Cavazzini, A. Santolin, G. Pavesi, and G. Ardizzon, "Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling," *Energy*, vol. 103, pp. 746–757, 2016, doi: 10.1016/j.energy.2016.03.024.